Cartographic Challenges in Antarctica: Mapping in Support of Environmental Management for the US Antarctic Program

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Abstract. Protecting the environment is a key principle in Antarctica, with protective measures agreed under the Antarctic Treaty System. Maps are an essential tool for environmental protection and management of Antarctic Specially Protected Areas (ASPAs) and Antarctic Specially Managed Areas (ASMAs). However mapping these remote sites presents a number of challenges such as inaccurate spatial frameworks, paucity of cartographic detail, the dynamic landscape and the need for international cooperation and consistency.

Keywords: Antarctica, Environmental Management, Protected Areas, Mapping, Cartography, Spatial Data, Remote Sensing

1. Introduction

The Antarctic Treaty was agreed in 1961 as a means to set aside territorial claims so that international activities in Antarctica could be conducted peacefully. The Protocol on Environmental Protection to the Treaty, agreed in 1991, declared Antarctica as a ‘natural reserve devoted to peace and science’ and provides a comprehensive framework of rules to guide environmental protection in the region. In this sense, the entire Antarctic region south of 60° S is ‘protected’, although it was recognized that more specific measures are needed at the site level. To achieve this, the Protocol provides for two types of special protection at particular sites, namely Antarctic Specially Protected Areas (ASPAs) and Antarctic Specially Managed Areas (ASMAs). ASPAs may be designated to protect sites of outstanding environmental, scientific, historic, aesthetic or wilderness values. ASMAs may be designated to assist planning and coordination at sites where a high concentration of activities occur.

Currently 72 ASPAs and seven ASMAs are designated in Antarctica. The majority of both ASPAs and ASMAs are situated near the coast and most are in close proximity to scientific stations (Figure 1). As one of 50 signatories to the Antarctic Treaty, the United States has proposed 14 of the ASPAs and five of the ASMAs adopted to date, some jointly with other Treaty Parties.

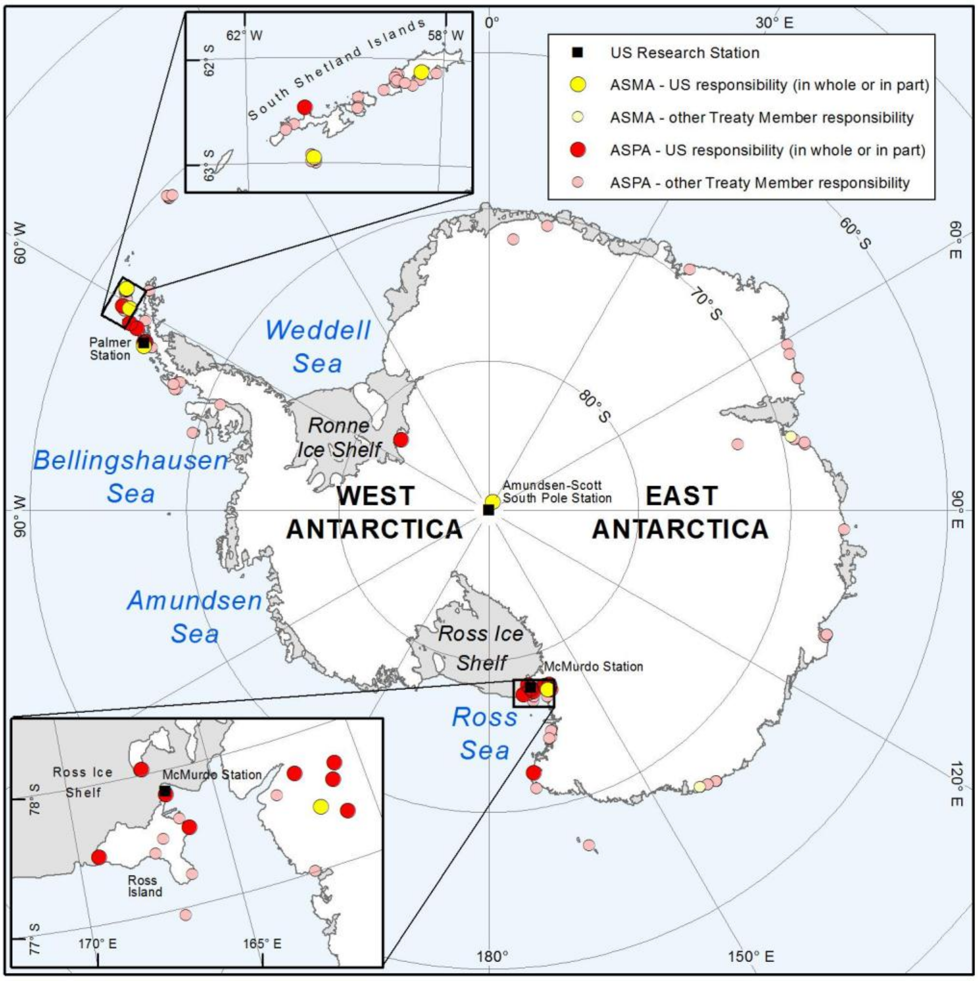

Figure 1. Overview of Antarctica showing spatial distribution of protected areas with full or part US responsibility for Management Plans and US stations

The Protocol requires Management Plans to be prepared for every ASPA and ASMA, and maps play a vital role by defining the boundaries, identifying the important features, and showing key management guidance (e.g. access rules) for these sites, which are often fragile and / or of unique scientific importance. Visitors to the sites rely on the detail and accuracy of the maps in order to carry out their activities both safely, scientifically reliably, and with due protection of the environment. Responsibility for the mapping falls to the Party or Parties that originally proposed the ASPA or ASMA, and the US prepares and maintains maps for the majority of sites for which it was one of the proponents.

The maps for these sites need to perform several functions. Simple overview location maps are needed to show where the site is in its regional context. Detailed large-scale maps are needed by those visiting the sites, so important features and management guidance are clear. Map development presents a range of cartographic challenges, such as dealing with inaccurate spatial frameworks, paucity of cartographic detail, the dynamic ice-dominated landscape, as well as challenges related to international cooperation and consistency.

2. Cartographic Challenges

2.1. Challenge 1: Inaccurate spatial framework

At the broad continental or regional level, small-scale maps of reasonable quality are widely available. However, when maps of scales larger than 1:200 000 are needed, as in the case for site management at ASPAs and ASMAs, spatial data of sufficient accuracy is usually lacking.

At medium scales (1:200K) and smaller, the Scientific Committee on Antarctic Research (SCAR) Antarctic Digital Database (ADD) is an important GIS dataset covering the entire Antarctic and is freely available (Thomson & Cooper 1993, SCAR 2013). The ADD is a vector dataset digitized from existing medium-scale topographic maps, supplemented by data digitized from satellite imagery, mostly Landsat. The ADD includes data on coastal features, contours, glacier margins, rock outcrops, lakes, spot heights and historic features. The data are available at 3 scales: 1: 10 M (10 level), 1: 1 M (1 level) and 1: 200 K/250 K (00 level).Version 6 of the dataset was published by SCAR in 2012 (SCAR 2013).

Original data forming the ADD were derived from maps prepared by a range of agencies using different methods at different times, which varied considerably in quality and content. Data from these sources needed to be integrated into a common spatial framework to achieve a seamless dataset across the region. As a result, the accuracy of the ADD is variable, and caution needs to be exercised when using the data. On the other hand, often this is the best map dataset available and is therefore frequently used for larger-scale applications even though it may not meet the accuracy standards generally accepted in other parts of the world.

Offsets of between 100 to more than 300 m can exist between the ADD and the actual geographical location of features. For example in the Palmer Station region (Arthur Harbor, Anvers Island, Antarctic Peninsula) the ADD 00 level data is offset by ~100 - 200 m (Figure 2), while at White Island (near McMurdo Station, Ross Sea) the offset is ~ 300 m.

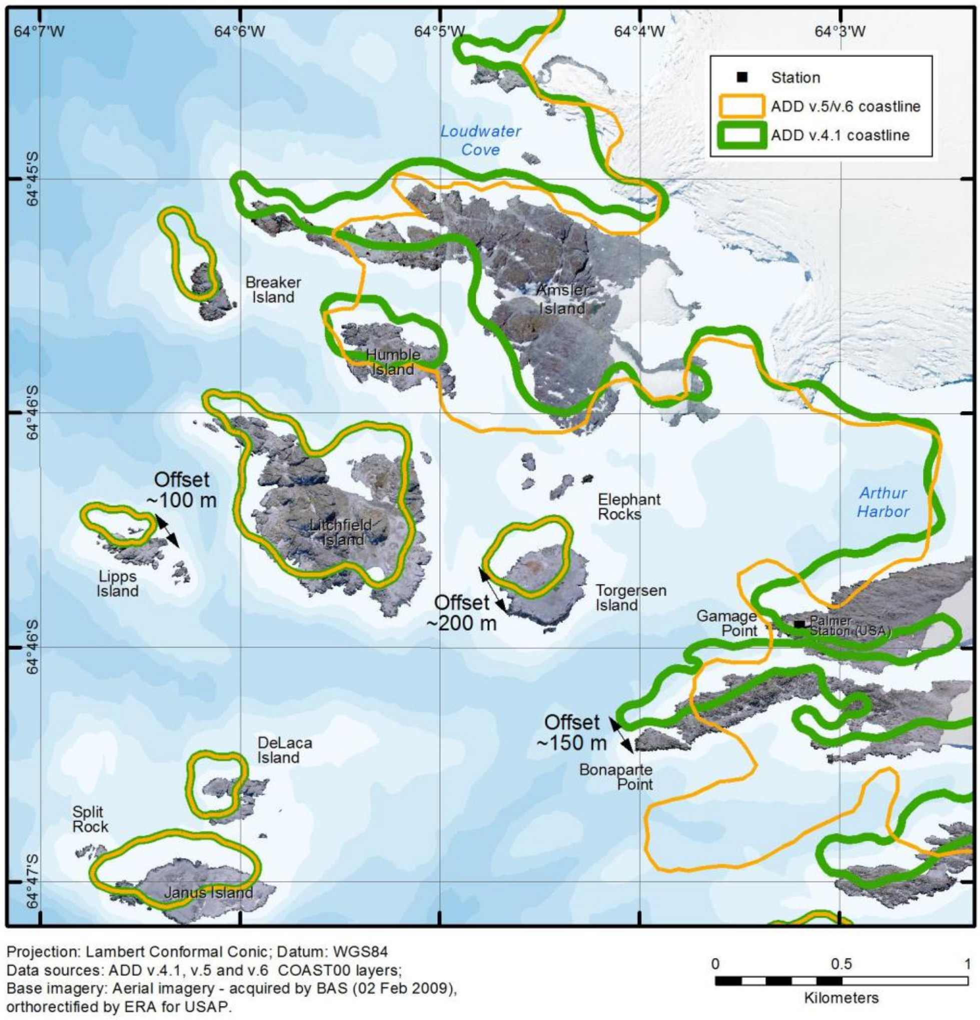

Figure 2. Inaccurate spatial framework: example of the offset between the ADD and high resolution orthorectified imagery at Palmer Station (ASMA No.7) (ERA in prep).

Within ASMA No. 2 McMurdo Dry Valleys vector data were digitized from 1: 50 K United States Geological Survey (USGS) Topographic Map Sheets, which were originally produced from aerial photography acquired in 1970 and 1983. The spatial framework for these data is more accurate than the ADD since the mapping was compiled at a larger scale. However, feature data generally suffer from a spatial offset of ~ 50 m from positions in new high resolution imagery that has been orthorectified using GPS control with sub-meter accuracy.

Therefore map makers and also map users need to be aware that modern GPS observations may not coincide precisely with features as depicted on the base maps.

In order to improve the positional accuracy of the spatial framework Ground Control Points (GCPs) need to be collected. GCP collection is often complex, time-consuming and costly because of the logistical challenges of accessing remote locations in the field. Some sites can require several days of ship or aircraft time to access. The harsh environment also presents challenges for technical equipment, with the cold and lack of available power sources in the field presenting particular constraints on instrument performance.

2.2. Challenge 2: Paucity of cartographic detail

The typical paucity of cartographic detail presents a further challenge for mapping in Antarctica. Considerable detail on site features is needed in Management Plan maps for environmental protection to be effective. Features often need to be mapped by precise ground based GPS surveys, since some features such as areas of vegetation, frequently comprised of sparse communities of sensitive mosses and lichens, are difficult to map from imagery and may occupy small areas of only a few square meters.

Precise mapping of coastlines can prove especially problematic, because access can be very difficult for ground survey, detailed imagery may not be available, and data on tidal ranges are usually not available. A particular problem exists in defining the coastline where it lies at the boundary between permanent ice shelves and the land, since the coastline is often not plainly visible at the surface. The coastline may be indicated by changes in ice slope, which can be subtle, or by cracks in the ice formed by flexing of the ice where it is grounded, although precise determinations of the ice grounding line may require more sophisticated methods such as Radio Echo Sounding.

To illustrate these issues, data from two versions of the ADD may be compared against orthorectified aerial imagery at Palmer Station (Figure 2). The ADD v4.1 coastline shows reasonable correspondence to the coastline evident in the imagery, taking into account that these data are more generalized and were intended for scales of 1:200 K. However, in ADD v5/v6 the quality of the coastline of Anvers Island is comparatively poor. In another example, a comparison was made against recent high resolution satellite imagery in the southern Argentine Islands, Antarctic Peninsula (Figure 3). A number of separate islands are evident in the recent satellite image. The main islands are faithfully separated in ADD v4.1, although the cartographic detail captured in the coastline is poor. However, in the more recent versions of the ADD (v5/v6), the coastline appears more detailed and yet several of the smaller islands have now, erroneously, been merged into one island. The method used to update these map features appears to have improved detail and accuracy in one way and yet degraded it in another. Unfortunately, the more recent version of the ADD in these cases has not resulted in an improvement.

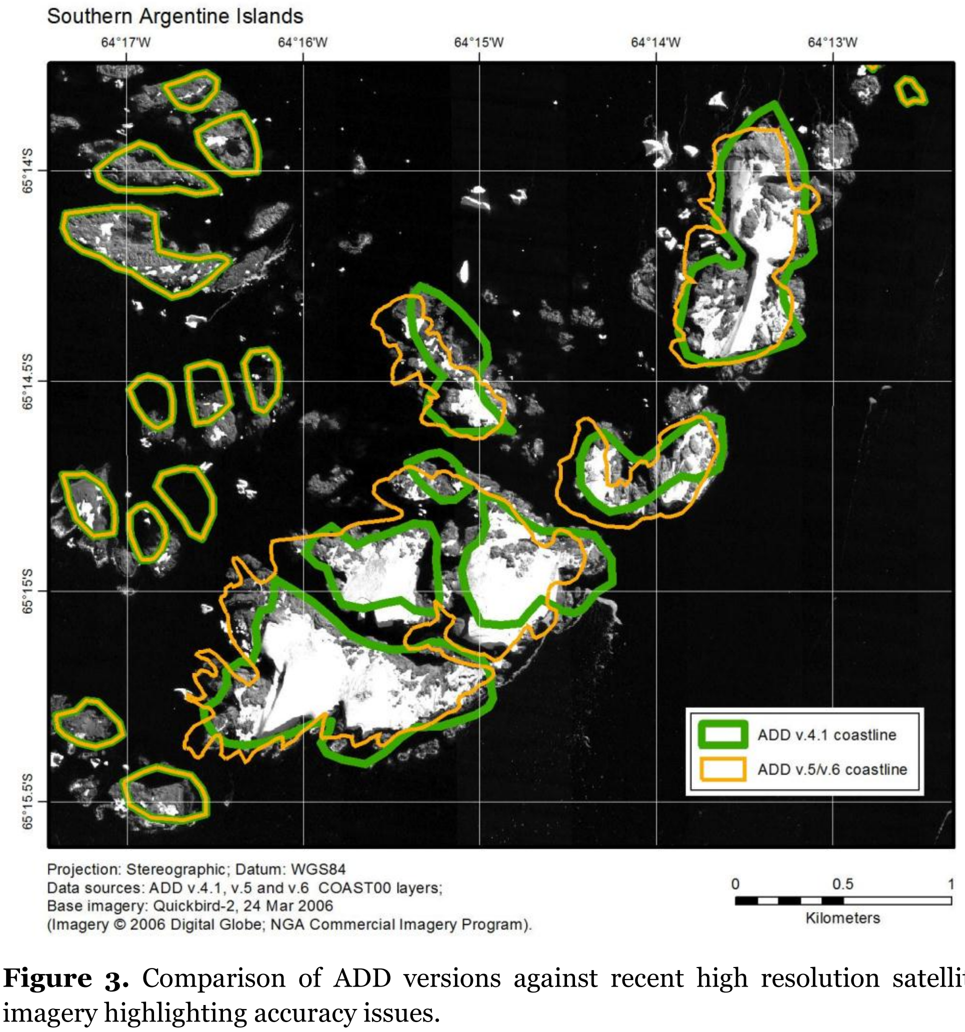

Figure 3. Comparison of ADD versions against recent high resolution satellite imagery highlighting accuracy issues.

Boundary definition of ASPAs and ASMAs is often closely connected to the topography. For example, the boundary of ASPA No 123 Barwick and Balham Valleys, in the McMurdo Dry Valleys, is defined based on valley catchments. A coarse Digital Elevation Model (DEM) inevitably leads to an imprecise definition of the catchment boundary. Since the boundary is a legal definition and visitors need permits to enter ASPAs, the legality of entry could be challenged when the boundary is only approximate or is wrong. To the extent that is practical, protected area boundaries should be defined to be clear, unambiguous and accurate, for which good quality mapping is essential. However, few high resolution DEMs are available in Antarctica, so in practice many protected area boundaries are poorly mapped and inaccurate.

The National Snow and Ice Data Center (NSIDC) has created the Radarsat Antarctic Mapping Project DEM Version 2 (RAMP DEM) based on data collected from satellite radar altimetry, airborne radar survey, the ADD and topographic maps. The RAMP DEM is intended for smaller scale mapping, and has a raster cell size resolution of 1 km, 400 m and 200 m (Liu et al 2001) which is insufficient for large scale mapping.

Publicly available data frequently used elsewhere in the world such as the Shuttle Radar Topography Mission (SRTM) DEM does not cover Antarctica, with coverage only extending to 54°S (van Zyl 2001). The ASTER Global DEM covers Antarctica, although suffers from errors perhaps as a result of the extensive snow and ice surfaces. In very limited areas such as the McMurdo Dry Valleys good quality LiDAR DEMs with post spacing of 2 m and 4 m are available with patchy coverage, which has been useful for orthophoto production (USARC 2004). However, even here, gaps exist in the DEMs which, depending on their size, can to be filled with approximate elevation estimates by using interpolation techniques or other lower resolution datasets such as the ASTER Global or RAMP DEMs.

2.3. Challenge 3: The dynamic landscape

The Antarctic is highly dynamic, with 99.66 % of the continent covered by a constantly moving ice sheet (Fox et al 1994). Features situated on the surface of the ice sheet are constantly moving at rates that vary from place to place, depending on the underlying topographic and glacial characteristics. For example, glacial movement at the South Pole is in the order of around 10 m per year (NSF 2013).Consequently, all facilities at the Amundsen-Scott South Pole Station shift by this amount relative to the South Pole every year, and as a result maps of the South Pole need to be frequently updated. Movement in other regions is much more rapid, for example the Whillans Ice Stream moves at a rate of ~700 m per year in some areas (Joughin et al 2002), although the need for frequent map updates is reduced because such dynamic sites generally lack permanent installations.

Where the ice sheet margin meets the sea, either as glacial ice or as a permanent floating ice shelf, the coastline is in a constant state of flux. Recently, rapid climate changes have led to the dramatic collapse of a number of ice shelves (Vaughan & Doake 1996, Velicogna 2009), and glacier front positions are generally in recession (Cook et al 2005). The Antarctic Peninsula has witnessed one of the most extreme changes in atmospheric temperature anywhere on the planet in the last 50 years, and warming here is substantially more rapid than the global mean (Turner et al 2005, Vaughan et al 2003). One of the more dramatic events was the collapse of the Larsen B Ice Shelf (3,250 km^2) which disintegrated within only a few weeks in early 2002 (NSIDC 2002, Rack & Rott 2004).

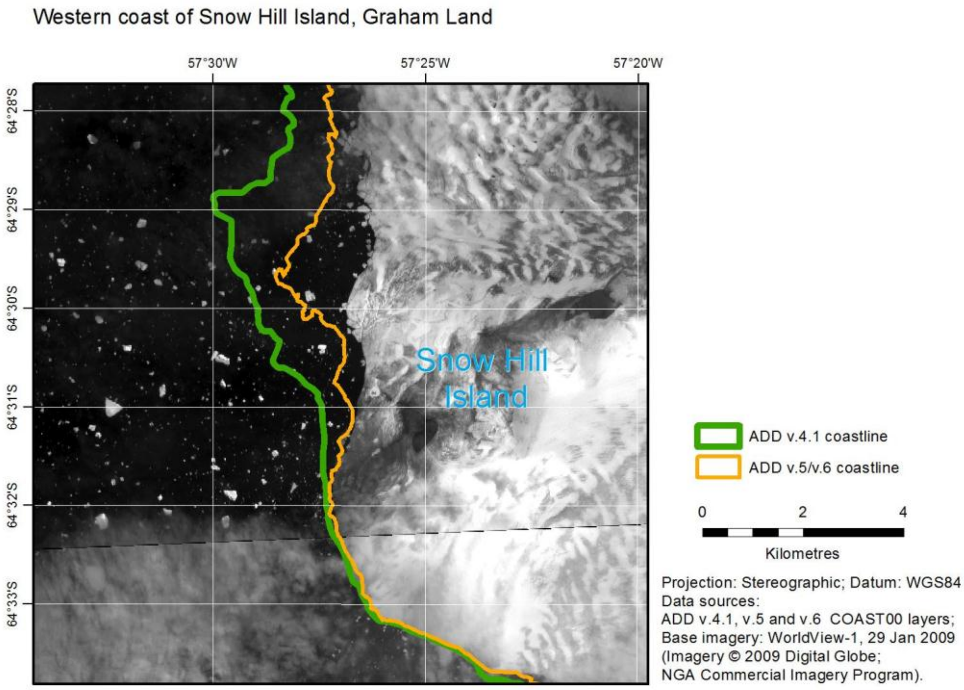

Figure 4: The dynamic Antarctic landscape: comparison of coastlines from the ADD (from maps (v4.1 date unknown), from Landsat imagery (v5/v6, 2000) against high resolution satellite imagery (WorldView-1 Jan 2009).

In a further example, the western coastline of Snow Hill Island, Graham Land, retreated by a distance of more than one kilometer over a period of only nine years between 2000 – 2009 (Figure 4). In Antarctica, therefore, even recently mapped data can become quickly outdated.

Seasonal changes in Antarctica present additional cartographic challenges. Sea ice and snow cover in the region changes dramatically between seasons, and when making maps from imagery it can be difficult to interpret which ice bodies are permanent versus those that are transitory. Some transitory ice fields may persist for several years, creating the impression of permanence. Observations over a number of years are sometimes necessary to distinguish permanent features reliably. Moreover, grounded icebergs can sometimes take on the appearance of small offshore islands in imagery, leading the unwary into charting them as permanent land features only to find they have disappeared several years later. This is particularly the case when using remote sensing rather than ground survey.

Antarctic wildlife is also highly dynamic. Large bird colonies such as penguins can witness substantial population changes between years and over longer time-scales. Moreover, the populations of most wildlife colonies are counted only sporadically, if at all, and much data on these populations are derived from surveys carried out up to 30 years ago (Croxall and Kirkwood 1979, Woehler 1993).This presents a challenge for map makers seeking to define the spatial extent of colonies, which may be important when making management decisions in ASPAs or ASMAs such as where to locate the position of a new facility, where to land an aircraft, or to define where access should be allowed.

2.4. Challenge 4: International cooperation and consistency

Unlike most terrestrial areas of the world, Antarctica is an international territory where claims to sovereignty are not universally recognized. Many countries operate in the region, working in overlapping geographical areas, and each may undertake mapping according to national procedures. In such a context, there is a need for international cooperation to achieve consistency. The challenge of coordination is taken up by SCAR through its Standing Committee on Antarctic Geographic Information, through cooperation between national mapping agencies and under the Antarctic Treaty. New Zealand and the United States, for example, have cooperated closley in mapping programs in the Ross Sea (Antarctica NZ & USAP 2011).

Spatial data are collected by numerous agencies, institutions and individuals operating in Antarctica and these data are widely dispersed. Under the Antarctic Treaty „scientific observations and results from Antarctica shall be exchanged and made freely available“, and yet data restrictions often still exist. Data are not always documented by metadata. Add language barriers, and in practice it can sometimes be difficult to identify and obtain spatial data, and good quality data that have been acquired might not be as widely used owing to inaccessibility.

In this international context, map symbols and place naming represent two further coordination challenges. A set of standard map symbols for use on small-scale maps was developed by SCAR as long ago as 1961, which were revised in 1980 (SCAR 1961, 1980). An updated guide on standard symbols was issued by the Australian Antarctic Division for use with 1:50K maps (AAD 1999). These symbols cover the main physical features likely to be needed at these scales, although at the larger scales that are needed for environmental management a wide range of features are not yet included (e.g. for breeding sites of different wildlife species, protected zones, emergency caches, wind generators, airstrips, etc.). In practice, such 'standard' symbols will need to be adapted in accordance with the type of map (e.g. image map or line map), and also in view of the needs of map users.

Place names in Antarctica may be assigned and formally adopted by any country in accordance with national procedures, and there is no requirement of international approval. Names adopted by one country are not necessarily recognized by others, as illustrated recently when the UK adopted the name Queen Elizabeth Land for large part of Antarctica which coincided with a region also claimed by Argentina; not surprisingly the Argentine government did not recognize the name. More usually, however, names adopted by countries may be mutually recognized as acceptable and the names adopted by a number of nations may appear on maps. Many features in Antarctica remain to be named, and it is common for large-scale maps to have only a few officially adopted names appear. SCAR has compiled a Composite Gazetteer of Antarctica, which helps to coordinate geographical naming by including all of the names officially adopted by the parties to the Antarctic Treaty (https://data.aad.gov.au/aadc/gaz/scar/).

3. Addressing the Challenges

The recent increasing availability of high resolution satellite imagery is revolutionizing mapping in Antarctica. Platforms such as Digital Globe's Worldview-1 and -2 and Quickbird-2 provide imagery with pixel resolutions of up to 0.46 m, which is becoming close to that which is achievable using conventional aerial survey cameras. The US Antarctic Program (USAP) has the benefit of free access to much of this imagery through an agreement under the US National Geospatial Agency (NGA) Commercial Imagery Program. Additionally, active sensors such as imaging Radar are providing data in a region where cloud cover is a persistent problem for optical sensors.

Orthorectification of imagery is still necessary to correct for geometric and terrain distortions, which can be considerable especially when images are acquired over steep terrain or at off-nadir angles up to ~25° or more. Within the USAP, the Polar Geospatial Center (PGC) and ERA have been developing new orthorectified image products to improve maps available for environmental management and to support science (Antarctica NZ and USAP 2011, PGC 2012A & 2012B, ERA in prep). This has required effort to acquire accurate ground control, and to build DEMs of sufficient resolution from stereo imagery. In recent years Radar and LiDAR has been used to generate DEMs, although their availability at the high resolution needed for large scale mapping is still very limited.

In some cases it is possible to improve positionally inaccurate maps by applying a simple x, y shift, the magnitude and direction of which being determined using a nearby known reference point. While the method may be crude, and assumes that the adjustment needed is constant across the map, it can yield a real improvement in the mapping where better data are otherwise lacking.

For example at ASPA No. 137 NW White Island, ADD 00 level data were spatially adjusted by ~260 m northeast so that it corresponded with the position of a more precise large-scale dataset that was available for an adjacent area. While far from perfect, this did mean that features on the map relative to accurate GPS observations were only 10s, and not 100s, of meters offset from their true positions. At Palmer Station an entirely new basemap derived from orthorectified aerial imagery and accurate sub-meter ground control (ERA in prep) replaced the old ADD v4.1 data, which has been shifted by ~110 m southeast to bring it into a position that is approximately correct so that it could be used as an interim map product while the new map was under development (Figure 5).

High resolution satellite imagery has also been used to assess and map wildlife populations. For example QB-2 and WV-1 images were used to detect the abundance and variation of Weddell seals in Erebus Bay, near Ross Island (LaRue et al 2011). While aerial photography has been used to count penguins for many years (Taylor et al 1990), even the latest commercial satellites are of inadequate resolution to count individual birds. However, a proxy has been used to estimate colony size for emperor penguins by quantifying the extent of guano stain, which the birds produce while breeding on sea ice (Fretwell et al 2012). It is not practical to achieve Antarctic-wide population assessments for these birds by conventional ground-based counts because of the remoteness of the colonies. However, other species nest amongst rocks where it is more difficult to distinguish a guano signature, and for them population assessment using satellite remote sensing remains elusive.

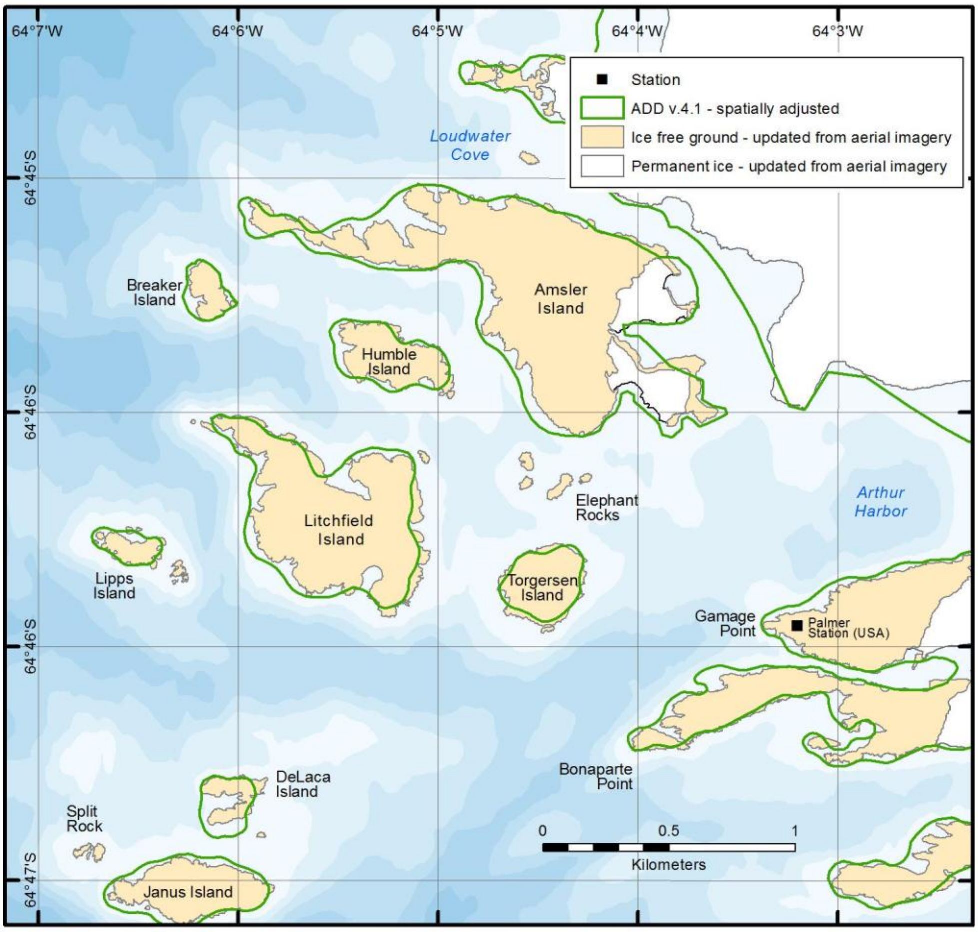

Figure 5: Example of improved basemap data at ASMA No. 7 Palmer Station, Arthur Harbor (ERA in prep).

A local coordinate system is used to map Amundsen Scott South Pole Station (US), located at the center of ASMA No. 5, to address the dual problems of the moving ice sheet and the fact that every direction from the South Pole is north. This local grid moves with the facilities and ice sheet as they move as a unit, thereby maintaining relative consistency between the map framework and local features. The exception is the South Pole itself, which remains in fixed position, and therefore the maps show the Pole as apparently 'moving' relative to facilities by about 10 m per year. The physical marker placed into the ice to designate the geographic South Pole is moved back to its correct position once every year after having moved with the ice.

4. Conclusion

Map production for environmental management in Antarctica, in particular to support management plans for ASMAs and ASPAs, faces a number of challenges. Prominent amongst them are the lack of spatial data available at large scales and that are georeferenced to accurate spatial frameworks. Recently high-resolution satellite imagery is becoming available which is already making a major contribution to addressing this problem. Nevertheless, the lack of good quality ground control and the general absence of high-resolution DEM data remain significant obstacles to map improvements. Substantial logistical challenges exist to gathering such data in the harsh and remote Antarctic environment, although increasingly accurate maps are being produced with a minimum of ground control with improvements in satellite-based data, including GPS. The dynamic landscape of Antarctica will persist as a mapping challenge, with the predominantly ice-covered environment constantly moving, and rapid changes to the ice sheet associated with a warming climate certainly present a challenge for keeping maps up to date.

Environmental management in Antarctica depends critically on the availability of good quality maps to identify features in need of special protection. Maps play a key role in management plans to represent these features, and to make operations, science and environmental protection in these areas both practical and effective.

Efforts to address the mapping challenges in Antarctica require considerable investment, and strong international cooperation and coordination. The long tradition of cooperation that exists under the Antarctic Treaty, and the new, high quality, spatial data emerging from new instrumentation, in particular from satellite platforms, are set to ensure that future Antarctic mapping will see some exciting and significant improvements in coming years. This should help in the protection of the unique and pristine environment of Antarctica.

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